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Review

Allelopathy for weed control in agricultural systems

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ABSTRACT

Weeds are a hidden foe for crop plants, interfering with their functions and suppressing their growth and development. Yield losses of ~34% are caused by weeds among the major crops, which are grown worldwide. These yield losses are higher than the losses caused by other pests in the crops. Sustainable weed management is needed in the wake of a huge decline in crop outputs due to weed pressure. A diversity in weed management tools ensures sustainable weed control and reduces chances of herbicide resistance development in weeds. Allelopathy as a tool, can be importantly used to combat the challenges of environmental pollution and herbicide resistance development. This review article provides a recent update regarding the practical application of allelopathy for weed control in agricultural systems. Several studies elaborate on the significance of allelopathy for weed management. Rye, sorghum, rice, sunflower, rape seed, and wheat have been documented as important allelopathic crops. These crops express their allelopathic potential by releasing allelochemicals which not only suppress weeds, but also promote underground microbial activities. Crop cultivars with allelopathic potentials can be grown to suppress weeds under field conditions. Further, several types of allelopathic plants can be intercropped with other crops to smother weeds. The use of allelopathic cover crops and mulches can reduce weed pressure in field crops. Rotating a routine crop with an allelopathic crop for one season is another method of allelopathic weed control. Importantly, plant breeding can be explored to improve the allelopathic potential of crop cultivars. In conclusion, allelopathy can be utilized for suppressing weeds in field crops. Allelopathy has a pertinent significance for ecological, sustainable, and integrated weed management systems.

1. Introduction

Weeds constantly compete with crop plants to cause a considerable loss in their productivity. Hence, weeds have been documented as serious plant pests since the ancient times (Zimdahl, 2013). Weeds have always played a role throughout the domestication of crop plants which necessitated practicing weed control measures (Oerke et al., 1999; Zimdahl, 2013). Pulling by hand, cutting, and physically smothering weeds were among the ancient methods of weed control (Oerke et al., 1999; Young et al., 2014). Over time, hand tools were developed to till soils in order to control weeds. During recent times, herbicides and other modern means of weed control have been used. However, since the beginning of agriculture, hand weeding, mechanical weeding, and herbicide applications have been the most relied upon weed control methods (Griepentrog and Dedousis, 2010; Bergin, 2011; Rueda-Ayala et al., 2011; Chauvel et al., 2012). These weed control methods have served to keep weed infestations low and improve the crop productivity throughout the world.

Despite the significant contribution of these weed control methods in improving crop productivity, certain challenges are also associated with them. Decreasing availability and increasing cost of labour, and inconsistent weed control are among the major challenges in hand weeding (Carballido et al., 2013; Gianessi, 2013). Similarly, mechanical weed control requires extra soil turn-over, which can disturb soil structure and deplete soil fertility (Smith et al., 2011). Mechanical weed control is not always effective and can be expensive and lack durability (Bond and Grundy, 2001). Likewise, herbicide-resistant weeds, health effects, and environmental concerns are the major constraints for repeatedly using herbicides for weed control (Annett et al., 2014; Hoppin, 2014;

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Powles, 2008; Starling et al., 2014). The challenges associated with conventional weed control methods (e.g., hand weeding, mechanical control, herbicides, etc.) make it imperative to develop diversity in the current weed control methods. A variety of options would be available for site specific weed control if diverse weed management methods are developed. The cost and ecological concerns can be firmly addressed by using diversified weed management options. Suppressing weeds by harnessing the allelopathic phenomenon is included among the important innovative weed control methods (Jabran and Farooq, 2013; Zeng, 2014). Plant hormones and defence mechanisms are manipulated to control weeds in different agro-ecosystems (Pickett et al., 2014).

This review article discusses the practical application of allelopathy for weed control in agricultural systems. Further, we have focused on the implications of weeds in crop production, challenges in weed management, potential allelopathic crops, and the use of allelopathy for managing weeds. Strategies, such as the use of allelopathic cultivars, intercropping with allelopathic weed suppressive plants, the use of allelopathic cover crops and residues, and rotational sowing of allelopathic crops, have been discussed for practical weed control in field crops.

2. Weeds and crop production

Weeds coincide spatially with crop plants. They deprive the crop plants from limited available nutrients, space, light, and moisture. Hence, the physiological activities and growth of crops are negatively affected in the presence of weeds (Rajcan and Swanton, 2001). Ultimately, poor crop productivity is the result, due to weed-crop competition.

Among all types of crop pests, weeds are known to cause the greatest yield reductions in the crops (Oerke et al., 1999). On an average, weeds can lower crop productivity by 34% (Oerke, 2006). The potential yield reductions by weeds in some important crops are: wheat 23%, soybeans 37%, rice 37%, maize 40%, cotton 36%, and potatoes 30% (Oerke, 2006).

Weeds have indirect effects on crop plants. Crop development is affected by allelopathy from certain weed species. Allelochemicals from allelopathic weeds can disturb the root and shoot growth of emerging crop seedlings, as well as cause several other damages. In a recent study, Dmitrović et al. (2014) reported that allelochemicals excreted from *Chenopodium murale* L. root hairs were responsible for the cell cycle disturbance and oxidative damage in wheat and *Arabidopsis thaliana* seedlings. Similarly, allelopathic water extracts from weed species, including *Malva parviflora* L. and *C. murale*, were shown to inhibit the growth and photosynthetic activity in barley (Al-Johani et al., 2012). The invasive weed *Flaveria bidentis* (L.) Kuntze was found to excrete allelopathic phenolic compounds (Zhang et al., 2012). Residues from this weed inhibited the growth and biomass of cotton seedlings. Weeds can also impact crop yield by serving as alternate hosts for many insect pests and plant diseases. Weeds can interfere with harvest of the crop in addition to elevating the cost of production from the cost associated with their control.

3. Challenges in weed management

With world population increasing and available resources decreasing, weed management is an even more important as well as a challenging job. Accurate weed control is compulsory for food security throughout the world. Currently, most reliable weed control methods include herbicide application, mechanical weeding, and hand weeding. However, the sustainability of long term chemical weed control is facing certain challenges. Most important among these challenges is the evolution of herbicide resistance in weeds. The other problems faced in weed management with herbicides are the negative impacts of herbicides on environmental, human and animal health. Most importantly, herbicides, with few exceptions, cannot be applied in fields in which crops are being grown organically. Under certain cases, small-scale farmers cannot afford the expense of herbicides. Mechanical weed control on the other hand, needs to be performed several times to achieve effective weed control. Mechanical weed control poses an economic and soil health expense, due to losses in soil structure. Hand hoeing is a weed control method largely followed throughout the world. This method though, requires an enormous amount of labour, and hence is difficult to practice on a large scale.

Several of the above problems with current weed management practices can be allayed by creating diversity in weed control practices. A dependence on more than one weed control method has proved to be effective in reducing the chances of herbicide resistance development in weeds. Further, using diverse weed management practices on certain fields can ensure sustainable and effective weed control. Thus, manipulating the allelopathic phenomenon can help to improve weed control in crops by harnessing the synergism to improve the efficacy of other weed control methods.

4. Potential allelopathic crops

Several plants express the allelopathic phenomenon through exudation of allelochemicals. For example, rye is among the most important allelopathic crops. Although benzoxazinones [2,4-dihydroxy-1,4(2H)-benzoxazin-3-one (DIBOA) and 2(3H)-benzoxazolinone (BOA)] are the most important allelochemicals responsible for the allelopathic potential of rye, several of other important allelochemicals are also present in rye. Recently, Schulz et al. (2013) reviewed the allelopathic potential of rye and listed 16 allelochemicals present in this plant. These allelochemicals included β-phenyllactic acid, protocatechuic acid, DIBOA (glucoside), vanillic acid, apigenin-glycosides, syringic acid, luteolinglucuronides, *p*-hydroxybenzoic acid, *p*-coumaric acid, benzoxazolinones BOA, cyanidin glycosides, β-hydroxybutric acid, isovitexinglucosides, DIMBOA (glucoside), gallic acid, and ferulic acid/conjugates. Further, a number of studies reported the allelopathic inhibition of other crops and weeds by rye (Bertholdsson et al., 2012; Didon et al., 2014; Macias et al., 2014). Although rye can be manipulated to suppress weeds in a cropping system as a rotational crop, cover crop, or mulch, using it as a cover crop is the most common method for weed control (Norsworthy et al., 2011; Tabaglio et al., 2013).

Sorghum is another important allelopathic crop. Extensive literature explains the allelopathic potential of sorghum and its implications in different cropping systems. The allelopathic activity of sorghum varies across cultivars, environmental conditions, and plant growth stages. Sorghum expresses its allelopathic activity through the production of several allelochemicals. Most important among these allelochemicals are hydrophobic *p*-benzoquinone (sorgoleone), phenolics, and acyanogenic glycoside (dhurrin) (Weston et al., 2013). Sorgoleone is the most potent allelochemical of sorghum exuded by its roots. Root hair cells are responsible for the production of sogoleone in sorghum plants (Weston et al., 2012). The allelopathic activity of sorghum can be manipulated for weed control by planting allelopathic cultivars, applying sorghum residues as mulch, using sorghum as cover crop and intercrop, or including sorghum cultivars in a crop rotation.

The Brassicaceae family has a strong allelopathic potential against other crop and weed plants (Haramoto and Gallandt, 2004). Brassicas produce the allelopathic compound glucosinolate throughout their plant parts (Fahey et al., 2001). However, the concentration of this allelochemical varies in different parts of the plant (Fahey et al., 2001). Glucosinolate is released into the environment through either volatilization or decomposition. After the release, glucosinolate is decomposed into several biologically active compounds, such as isothiocyanate (Morra and Kirkegaard, 2002). Further, these allelochemicals (isothiocyanates) suppress the growth and development of plants/weeds which take them up (Petersen et al., 2001). The allelopathic potential of brassica plants can be used to suppress weeds by using the brassica plants as cover crops, intercropping brassica crops with the main crop, crop rotation, or the use of brassica litter as mulch (Haramoto and Gallandt, 2005; Rice et al., 2007; Bangarwa and Norsworthy, 2014).

Sunflower is considered the most important allelopathic crop. Sunflowers can be phytotoxic to the following crop in a cropping rotation. Several weed species have also been reported to be suppressed by sunflower allelopathy. Recently, Alsaadawi et al. (2012) evaluated the allelopathic potential of eight sunflower cultivars against problem weed species in wheat. They either grew the allelopathic sunflower cultivars in a mixture with weeds, or applied the residues (600 or 1400 g m^{-2}) of sunflower cultivars to the wheat crop and its weeds. The sunflower cultivars in the study varied in their allelopathic potential and suppressed total weed density by 10–87% and total weed biomass by 34–81%. Sunflower residues also expressed their allelopathic potential to suppress total weed density (24–75%) and total weed biomass (12–67%), and increased wheat grain yield and yield components over the non-treated control. Further, 16 allelochemicals (phenolic acids) were found across the tested sunflower cultivars. The cultivars which suppressed weeds possessed higher concentrations of allelochemicals (Alsaadawi et al., 2012).

In conclusion, several crops have strong allelopathic potential, which is expressed through the exudation of a diversity of allelochemicals. The allelopathic potential of these crops can be manipulated to suppress weeds.

5. Allelopathic weed control

Practical weed control can be achieved by using allelopathy. Importantly, such weed control will neither harm the environment nor increase weed management costs. Allelopathic weed control may be applied as a single strategy in certain cropping systems, such as organic farming. Further, it can be combined with other methods to achieve integrated weed management. Under allelopathic weed control, the allelopathic potential of crops is manipulated in such a way that the allelochemicals from these crops reduce weed competition. The living plants or their dead materials express the allelopathic activity through the exudation of allelochemicals. The processes for exudation of allelochemicals are: root exudation, leaching from dead or live plant tissues, and volatilisation from the aboveground plant parts. Several factors help the movement of allelochemicals to target species. Soil hyphae are important allelopathic transporters. Achatz and Rillig (2014) argued that arbuscular mycorrhizal fungi were involved in facilitating the movement of below ground allelochemicals. The presence of soil hyphae at the time of application of the allelochemicals from *Juglans regia* L. caused growth suppression of the tomato test crop. The transportation of juglone allelochemical was increased in the presence of soil hyphae.

Allelopathic weed control can be implemented by growing allelopathic plants in close proximity to weeds which promote production of these chemicals (Tesio and Ferrero, 2010); or by placing the allelopathic materials obtained from dead plants in close proximity to weeds. The decomposing plant material releases allelochemicals which are absorbed by the target weeds. The most important example for such cases includes the use of allelopathic plant residues for weed control (Tabaglio et al., 2008). Allelopathic weed control can also be implemented by growing allelopathic plants in a field for a certain period of time, in order for their roots to exude allelochemicals. Crop rotation is the most important example for such allelopathic weed control (Farooq et al., 2011). Another way to control weeds through allelopathy includes obtaining allelochemicals in a liquid-solution by dipping the allelopathic chaff in water for a certain period of time. Several researchers have advocated using this way of weed control either alone or in combination with other methods of weed control (Jabran et al., 2010; Khan et al., 2012; Razzaq et al., 2010, 2012). Recent research indicates that allelopathic plants not only suppress weeds but can have positive effects on the soil environment, that is, improved nutrient availability to crop plants through and enhanced soil microbial activities (Wang et al., 2013; Zeng, 2014). The allelopathic wheat cultivar 22 Xiaoyan was found to have higher concentrations of microorganisms and enzyme (catalase and urease) activity (Zuo et al., 2014). The authors argued that the allelopathic wheat cultivars exuded carbon and nitrogen, which improved the allelopathic effects of soil microorganisms in the rhizosphere. Hence, the allelochemicals excreted from the microorganisms further helped to suppress crop weeds and diseases (Zuo et al., 2014).

In the following sections, we have discussed various ways for practical implementation of allelopathic weed control.

5.1. Allelopathic cultivars

Crop cultivars demonstrating high productivity in farmers' fields are commercially acceptable. At the same time, the capability of crop cultivars to suppress weeds is being considered as a preferred criterion for cultivar selection in many parts of the world (Kong et al., 2011; Worthington and Reberg-Horton, 2013). The allelopathic potential of crop plants contributes to the weed suppressing ability of cultivars. Table 1 summarises important studies narrating the allelopathic crop cultivars and the weeds suppressed by them in various parts of the world. Preferring weed-suppressive allelopathic cultivars over non-allelopathic cultivars can reduce weed infestation without incurring any extra cost, and would help to improve the efficacy of inputs and the method of weed control.

A number of studies clearly elaborate the importance of sowing allelopathic cultivars in reducing weed pressure. Mahajan and Chauhan (2013) highlighted the importance of cultivars' allelopathic potential for managing weeds in aerobic rice. In Korea, Ahn et al. (2005) investigated the allelopathic activity of 78 local rice cultivars against the most notorious rice weed *Echinochloa crus-galli* (L.) P. Beauv. A number of rice cultivars were found to decrease the biomass, number of tillers, and height of the weed under field conditions. Six out of 78 cultivars had an average *E. crus-galli* inhibition of above 40% (Table 1). In another study, Chung et al. (2006) evaluated the allelopathic potential of 99 rice cultivars. Five rice cultivars reduced weed germination and growth by more than 50%, while the other five by 40–50%. The rice cultivars which exhibited higher reductions in growth and germination of weeds were found to possess higher concentrations of allelochemicals, including momilactone A and momilactone B. Similarly, in China, five commercial rice cultivars were crossed with allelopathic cultivar (PI312777) in order to produce weed-suppressive allelopathic commercial cultivars (Kong et al., 2011). Among the resultant cultivars, Haugan-3 was found to be the high yielding (5.95 t ha^{-1}) as well as the most weed-suppressive (26–39%) cultivar. Ultimately, this weed-suppressive allelopathic cultivar (Haugan-3) was recommended for commercial cultivation in China (Kong et al., 2011).

Sun et al. (2012) compared the rice-*E. crus-galli* interactions in allelopathic (PI312777) and non-allelopathic (Liaojing-9) rice

Table 1
The allelopathic crop cultivars suppressive to weeds.

Crop	Allelopathic cultivars	Weed/test species suppressed	Allelochemicals	Weed suppression (%)	Country	References
Barley	Alexis Baronesse	*Lolium perenne* L.	–	–	Sweden	(Bertholdsson, 2005)
	Athinaida	*Echinochloa crus-galli* (L.) P. Beauv., *Setaria verticillata* (L.) P. Beauv.	–	83	Greece	(Dhima et al., 2006)
	Alpha	*Papaver rhoeas* L., *Veronica hederifolia* L.	–	58	Greece	(Dhima et al., 2008)
	Esterel			53		
	Lignee 640			59		
	Tersey			50		
	Scarleta			68		
	Galt Brea			65		
Canola	Av-opal, Pak85388-502, Roy98310, Roy47-99P1, JC134, Sardi603, Atr-beacon, Rivette	*Lolium rigidum* Gaudin	–	Root inhibition = 47–55; Shoot inhibition = 15–23	Australia	(Asaduzzaman et al., 2014)
Rice	Huagan-3	*E. crus-galli*, *Cyperus difformis* L., *Cyperus iria* L., *Lindernia procumbens* Philcox, *Alternanthera sessilis* R. Br., *Eclipta prostrata* (L.) L., *Leptochloa chinensis* (L.) Nees, *Monochoria vaginalis* (Burm. F.) Presl ex Kunth	–	26–39	China	(Kong et al., 2011)
	PI312777			27–51		
	Buldo	*E. crus-galli*	–	56	Korea	(Ahn et al., 2005)
	Agudo	*E. crus-galli*	–	54	Korea	(Ahn et al., 2005)
	Jaeraejongna	*E. crus-galli*	–	47	Korea	(Ahn et al., 2005)
	Dabaegjo	*E. crus-galli*	–	47	Korea	(Ahn et al., 2005)
	Geumjeom do	*E. crus-galli*	–	47	Korea	(Ahn et al., 2005)
	Baekjicheongbyeo	*E. crus-galli*	–	43	Korea	(Ahn et al., 2005)
	Noindari, Baekna, Baekgwangok	*E. crus-galli*, *Monochoria vaginalis*, *Scirpus juncoides*, *Eleocharis kuroguwai*	Momilactone A, momilactone B	>50	Korea	(Chung et al., 2006)
	Hinohikari	*Lactuca sativa* L.	Momilactone B	75	Japan	(Kato-Noguchi et al., 2010)
	Nipponbare			62		
	Sasanishiki			63		
	Yukihikari			60		
	Norin 8			51		
	Janganbyeo	*E. crus-galli*	*p*-hydroxybenzoic acid	79–94	Korea	(Chung et al., 2002)
	BR17	*E. crus-galli*	2,9-dihydroxy-4-megastigmen-3-one	45	Bangladesh	(Salam et al., 2009)
		Digitaria sanguinalis (L.) Scop.		4.2???		
		E. colona		42		
	Dinorado	*E. crus-galli*	Phenolic acids	60	Iran	(Berendji et al., 2008)
	Neda			45		
	Domsrokh			40		
	Dular			36		
	Mehr			34		
	Usen			30		
	OM 5930	*Lepidium sativum* L., *Leptochloa chinensis*, *E. crus-galli*	*N-trans*-cinnamoyltyramine	–	USA-Vietnam	(Le Thi et al., 2014)
	Super Basmati	*Triticum aestivum* L., *Trifolium alexanderum* L., *Hordeum vulgare* L., *Avena sativa* L.	-	–	Pakistan	(Farooq et al., 2008)
Rye	Wheeler	*Amaranthus retroflexus* L., *Eleusine indica* L. Gaertn.	DIBOA	5–95	USA	(Reberg-Horton et al., 2005)
Wheat	Vinjett	*L. perenne*	–	–	Sweden	(Bertholdsson, 2005)
	Rohtas 90 V6007 Pak 81 AS 2000 V7189 Bhakkar 2002 V6111 Chanab 2000 V6034 Uqab 2000 V4611	*A. fatua*	–	42–83	Pakistan	(Mahmood et al., 2013)
	22 Xiaoyan Sin-Altheeb Coupon	*Descurainia sophia* (L.) Webb ex Prantl	–	–	China	(Zuo et al., 2014)
	Tasman	*L. rigidum*	–	–	China	(Wu et al., 2003)
Sorghum	Enkath	*Sorghum halepense* L., *Cyperus rotondus* L., *Echinocloa colona* L. (Link), *Convolvulus arvensis* L., *Portulaca oleracea* L.	–	23–44	Iraq	(Al-Bedairy et al., 2013)

Table 1 (*continued*)

Crop	Allelopathic cultivars	Weed/test species suppressed	Allelochemicals	Weed suppression (%)	Country	References
Sunflower	Sin-Altheeb	-	Phenolic compounds	74	Iraq	(Alsaadawi et al., 2012)
	Coupon			81		
	Shabah			61		
	Zahrat Al- Iraq			53		
	Suncross-42	*Rumex dentatus* L., *Chenopodium album* L.	–	57–67%	Pakistan	(Anjum and Bajwa, 2008)

cultivars. Both types of cultivars reduced the biomass of *E. crus-galli* over the control; however, the reduction in biomass was ~33% higher by the allelopathic cultivars. The authors reported that the difference in the weed suppression activity of allelopathic and non-allelopathic cultivars was governed by the release pattern of the growth promoting allelochemical allantoin. The allelopathic rice cultivars could sense the presence of *E. crus-galli* and hence released allantoin in lower concentrations, which led to the poor growth of *E. crus-galli* plants adjacent to allelopathic rice cultivars (Sun et al., 2012). In contrast, Gealy et al. (2013) reported that the allelopathic rice cultivars had higher tillering and developed an extensive and strong root system than the non-allelopathic cultivars. The authors argued that this strong root system helps the allelopathic cultivars to distribute allelochemicals extensively, which ultimately suppressed weed growth. In another study, 73 cultivars of rice from Vietnam were evaluated for their allelopathic activity against *E. crus-galli* (Khanh et al., 2009). Out of the tested cultivars, a few (Khau Van, Y-1, and NhiUu) were effective in suppressing *E. crus-galli* under greenhouse conditions, while the other one (PhucTien) was effective under field conditions.

Wheat is among the most important food crops of the world. Wheat cultivars are available with allelopathic potential, thus work is in progress to screen wheat cultivars with allelopathic potential from the already existing gene pool. Work is also in progress to develop new allelopathic wheat cultivars through classical and modern breeding (Fragasso et al., 2013). For example, Mahmood et al. (2013) investigated the allelopathic activity of 35 Pakistani wheat cultivars against *Avena fatua* L. The tested cultivars expressed a variable allelopathic activity against *A. fatua*. Out of these 35 cultivars, 11 showed a high allelopathic activity, that is, 42–83% (Table 1).

In another study in Australia, Asaduzzaman et al. (2014) collected 70 rape seed cultivars from all over the world and evaluated their allelopathic potential by growing them in close proximity to *Lolium rigidum* Gaudin. Rape seed was sown at three densities, that is, 10, 20, and 30 plants per pot. Generally, higher density of rape seed resulted in higher suppression of *L. rigidum*. The cultivars with greater allelopathic activity (than the other cultivars in the experiment) were Barossa, Cescaljarni-repka, Pak85388-502, Av-opal, BLN3343CO0402, and Rivette. The authors concluded that the rape seed cultivars, which expressed higher allelopathic potential in this study can be used for weed suppression.

Reberg-Horton et al. (2005) evaluated 10 rye cultivars for their allelopathic potential. All the cultivars possessed the allelochemical DIBOA, which is responsible for the allelopathic potential of rye. The concentration of DIBOA was variable, depending on the management practices, growth stage, and plant life duration. Cultivar Wheeler had the highest concentration of DIBOA with a long lasting impact. The authors concluded that the prolonged allelochemical retention from the cultivar Wheeler would result in effective and durable weed control.

Although significantly influenced by environmental factors, the allelopathic potential of crop cultivars is a genetically controlled process. The allelopathic potential of crop cultivars against weeds can be increased through the breeding process. As a first step, the crop germplasm can be screened for its allelopathic potential. However, a weed suppressive allelopathic cultivar should also be high yielding. After selecting cultivars with desired traits, the genomic approaches can be applied for characterizing the relevant genes.

Various scientists around the world have conducted bioassays to find crop cultivars with allelopathic potential. For example, Pheng et al. (2009) conducted a bioassay, in which they tested the allelopathic potential of 395 rice lines from Cambodia against *E. crus-galli*. Fifteen out of 395 cultivars were found to suppress the weed in the bioassay. In the second part of the experiment, the authors screened 96 rice lines for their allelopathic potential, out of which 14 suppressed *E. crus-galli*.

Breeding efforts to improve the allelopathic potential of various crops are on record. For example, the allelopathic rice cultivar PI312777 was crossed with several of available commercial cultivars by Kong et al. (2011). In the F_8 generation, two breeding lines (Haugan-1 and Haugan-3) were found with high allelopathy against weeds; hence, these lines were evaluated for agronomic characteristics and weed suppression under field conditions. The three-year study indicated that the cultivars Haugan-1 and Haugan-3 effectively suppressed weeds, including *E. crus-galli* and *Cyperus* spp. Haugan-3 was found to be more suppressive against weeds and higher yielding than Haugan-1 and other cultivars in the experiment. Hence, this cultivar was released for commercial cultivation in China and was designated as the first allelopathic rice cultivar in China (Kong et al., 2011).

These studies suggest that some of the crop cultivars possess allelopathic potential while others do not. The crop cultivars with allelopathic potential can be grown for inexpensive, easy, and environment friendly weed control.

5.2. *Intercropping with allelopathic weed suppressing plants*

Compatible crops are grown together in order to harvest higher net yield and economic benefits. Further, growing crops in mixtures improves resource (land, water, nutrients, and light) use efficiency. In addition to these benefits, intercropping can be used to suppress weeds for environment friendly and economical weed control (Makoi and Ndakidemi, 2012). In particular, crops with allelopathic potential when intercropped with other crop plants help to reduce weed intensity, and hence improve crop productivity. For instance, intercropping maize and cowpea on alternate ridges helped reduce weed [*Echinochloa colona* (L.) Link., *Portulaca oleracea* L., *Chorchorus olitorius* L., and *Dactyloctenium aegyptium* (L.) Willd.] intensity by ~50% as well as improve land use efficiency (Saudy, 2015). In another study, the relay-intercropping of legumes with wheat was evaluated for weed suppression in comparison with the sole wheat crop (Amossé et al., 2013). The intercrops in the experiment included white clover, black medic, alfalfa, and red clover. The intercrops not only helped to suppress weeds compared with the sole wheat crop, but also reduced weed density in the following crop while red clover was the most effective intercrop for suppressing weeds in organically grown wheat.

Orobanche spp. are among the notorious weed parasites, which severely damage different crops. Allelopathic activity of berseem can be exploited through intercropping to suppress *Orobanche* spp. Fernández-Aparicio et al. (2010) reported that intercropping berseem with legumes (broad bean and pea) reduced the intensity of *Orobanche crenata* Forssk. Kandhro et al. (2014) evaluated intercropping of two allelopathic crops (sorghum and sunflower) for weed management in cotton. Both intercrops suppressed weeds in cotton by 60–62%, which resulted in a 17–22% increase in seed cotton yield. Sorghum and sunflower were also harvested for grains, which resulted in improved crop productivity, land utilization, and economic benefits.

A research trial was conducted in five European countries (Italy, UK, Denmark, France, and Germany) in order to evaluate weed suppression and other benefits of intercropping in comparison with a sole crop (Corre-Hellou et al., 2011). Barley was intercropped with peas (main crop) and compared with the sole pea crop in terms of weed suppression. *Chenopodium album* L. and *Sinapis arvensis* L. were the two dominant weed species in the experimental sites. Pea-barley intercropping reduced weed intensity and weed biomass compared with the sole pea or fallow plots. Moreover, weeds in the experiment were found to draw higher quantities of nitrogen (30%) in the sole pea crop than the pea-barley intercrop (10%) (Corre-Hellou et al., 2011). Therefore, intercropping allelopathic crops with the main crop can help to reduce weed intensity and improve yield gains.

5.3. Allelopathic cover crops

Cover crops are grown with the aim of maintaining the sustainability of an agro-ecosystem. Various objectives of growing cover crops include improving soil fertility and soil quality, and suppressing weeds and plant pathogens. Cover crops with allelopathic potential can suppress weeds. Several of the important cover crops include canola, rape seed, cereal rye, crimson clover, wheat, red clover, brown mustard, oats, cowpea, fodder radish, annual ryegrass, mustards, buckwheat, hairy vetch, and black mustard. Some of the cropping systems (e.g., organic cropping) heavily rely on cover cropping for weed management (Mirsky et al., 2013). The observations from farmers' fields and the results of experiments indicated that the release of allelochemicals from allelopathic cover crops and their physical effects were responsible for weed suppression in conservation organic farm fields (Altieri et al., 2011). Further, cover crops also possess several additional benefits other than weed management. For example, the results of a recent study indicated that along with suppressing weeds, the cover crops also improved soil moisture retention, soil fertility, and crop productivity (Altieri et al., 2011). Mixtures of cover crops have been found more effective in suppressing weeds compared to a single cover crop. Using more than one cover crop can produce higher quantities of diverse allelochemicals as well as higher biomass to suppress weeds more effectively. Important cover crops, main crops, and weeds suppressed by these cover crops have been summarised in Table 2.

Haramoto and Gallandt (2004) explored the role of brassica cover crops including white mustard and rape seed for weed suppression in agricultural systems. The authors argued that the brassica species exude allelochemicals, which are named glucosinolates. In natural environments, glucosinolates are decomposed into several compounds, most important of which are isothiocyanates (Halkier and Gershenzon, 2006). Isothiocyanates are biologically active and suppress the germination and growth of exposed plant species (Norsworthy and Meehan, 2005). The effects of brassica plants were more pronounced on germination of weed species than on their growth (Haramoto and Gallandt, 2004). The allelopathic effects of the brassica plants may be carried to the succeeding crops, which can be avoided through careful selection of the cover and the succeeding crops.

Cover crops are also useful in conservation tillage systems to effectively suppress weeds. For example, Bernstein et al. (2014) tested the efficacy of a rye cover crop to suppress weeds for planting soybean under a no-till system and concluded that soybean could be successfully sown in a standing rye cover crop in a no-till soil. Planting soybean in a standing rye crop resulted in long-lasting and effective weed control with no damage caused to the soybean crop. Similarly, rye and wheat cover crops helped to improve weed control in glyphosate-resistant cotton under a conservation till system (Norsworthy et al., 2011). Biomass of weeds including *Eleusine indica* (L.) Gaertn., *Amaranthus palmeri* S. Wats, and *Ipomoea lacunose* L. was reduced by the cover crops, which helped to acquire season-long weed control. Moreover, cover crops can also reduce the weed seed bank in conservation till systems. For example, the cover crops hairy vetch and oat effectively reduced seed banks (30–70%) of weeds, including *Datura stramonium* L.,

Table 2
Allelopathic cover crops, main crops and the weeds suppressed by cover crops.

Cover crop	Main crop	Weeds suppressed	References
Wheat	Cotton	*E. indica*, *Amaranthus palmeri* S. Wats, *Ipomoea lacunosa* L.	(Norsworthy et al., 2011)
Rye	Cotton	*E. indica*, *A. palmeri*, *I. lacunosa*	(Norsworthy et al., 2011)
Rye	Soybean	*C. album*, *Abutilon theophrasti* Medik.	(Bernstein et al., 2014)
Annual ryegrass, rye, bristle oat, common vetch, radish	Common bean, tomato	*Brachiaria plantaginea* (Link) Hitchc., *Ipomoea grandifolia* (Dammer) O'Donell, *Bidens pilosa* L., *Euphorbia heterophylla* L.	(Altieri et al., 2011)
Hairy vetch, oat	Maize	*D. sanguinalis*, *E. indica*, *A. retroflexus*, *Datura stramonium* L.	(Dube et al., 2012)
Sorghum sudangrass [*Sorghum bicolour* (L.) Moench × *Sorgum sudanense* (Piper) Staph.]	Broccoli	Broad leaved weeds	(Finney et al., 2009)
Bristle oat, hairy vetch	Cotton	*A. palmeri*, *P. oleracea*, *Helianthus annuus* L.	(Moran and Greenberg, 2008)
Rye, hairy vetch, barley × triticale, Austrian winter pea	Organically grown maize-soybean	*C. album*, *Amaranthus hybridus* L., *Thlaspi arvense* L., *Taraxacum officinale* (L.) Weber ex F.H.Wigg., *Stellaria media* (L.) Vill., *Elymus repens* (L.) Gould, *Panicum crus-galli* L., *Setaria glauca* (L.) P. Beauv.	(Silva, 2014)
White mustard	Olive groves (*Olea europaea* L.)	*Amaranthus blitoides* S.Watson, *C. album*	(Alcántara et al., 2011)
Hairy vetch, subterranean clover, oat/hairy vetch	Tomato	*A. retroflexus* and *C. album*	(Campiglia et al., 2010)

Digitaria sanguinalis (L.) Scop., *Amaranthus retroflexus* L., and *E. indica* in the upper soil layer (Dube et al., 2012). In conclusion, several of allelopathic cover crops can help to reduce weed infestation in field crops.

5.4. Allelopathic plant residues

In most cases, specific parts of crops are used for consumption, while the rest of plant portions are fed to animals, discarded, or incorporated in the soil as organic matter. For example, wheat, maize, and rice are salient grain crops whose grains are consumed as food while other plant parts are either fed to animals or left in the field. Similarly, cotton is the salient fibre crop of the world whose seed cotton is obtained for industrial uses while the rest of plant parts are either discarded or left in the field. Allelopathic plant residues left in the field either unintentionally or added manually express their activity to suppress weeds. For example, the plant residues of barley, rye, and triticale retained in a maize field were evaluated for their allelopathic effect against *E. crus-galli* and *Setaria verticillata* (L.) P. Beauv. in Greece (Dhima et al., 2006). The allelopathic mulches decreased the emergence of *S. verticillata* (0–67%) and *E. crus-galli* (27–80%) compared with the non-mulched treatment. The maize plants received no harmful effect from the applied mulches. The grain yield of maize was increased by 45% in the plots applied with barley mulch compared with the ones with no mulch (non-treated control) (Dhima et al., 2006). Similarly, the maize residues incorporated in an organically grown maize-broccoli rotation were found to reduce weed biomass in the following crop (broccoli) by 22–47% (Bajgai et al., 2013). The incorporated mulch also helped to improve the soil nutrient status. Similarly, in another study, tomato seedlings were transplanted in mulch residues of three crops (oat, hairy vetch, and subterranean clover) (Campiglia et al., 2010). The mulches were effective in suppressing weeds (35–80%) in terms of density and biomass over the control treatment, while oat was the most effective among the mulches in suppressing weeds. However, oat also negatively affected tomato yield. Nevertheless, the highest increase in yield over the control resulted from hairy vetch. In a similar study, the residue mulch of oat and hairy vetch effectively reduced weed density (*A. retroflexus*, *Polygonum aviculare* L., *P. oleracea*, and *C. album*) in black pepper (Campiglia et al., 2012). Oat was more effective against weeds than hairy vetch; however, hairy vetch resulted in a higher increase in black pepper yield than oat.

A diversity in allelopathic materials can improve the allelopathic activity against weeds owing to the presence of diverse allelochemicals. Also, the synergistic effect of allelochemicals can improve their activity against target weeds. Based on this hypothesis, Khaliq et al. (2010) applied a combination of allelopathic plant residues, including sunflower, canola, and sorghum, at 7.5 t ha^{-1} for weed control in a maize crop. The applied mulch reduced the densities and biomass of *Cyperus rotundus* L. and *Trianthema portulacastrum* L. by ~90% and increased maize grain yield, 1000-grain weight, and harvest index by 54%, 13%, and 29%, respectively. No negative effect of the applied mulch material was reported on the growth or development of maize which implies that the allelopathic materials could be used for weed control without damaging maize plants (Khaliq et al., 2011).

In conclusion, allelopathic plant residues can be applied as mulch to suppress weeds and improve grain yield. Enhanced moisture conservation and nutrient availability are additional benefits of using mulches for weed management.

5.5. Inclusion of allelopathic crops in rotation

Crop rotation is the sequence or arrangement of crops sown on a certain field. The objective of this sequence is to maintain soil productivity and sustainability. Certain changes in this crop sequence can reduce pest infestations. Crop rotation alone lowers weed infestation in crop fields while it enhances the effectiveness of weed control when combined with other methods (Garrison et al., 2014). For example, crop rotation was among the major weed control strategies used by organic growers in New York, USA, to suppress weeds (Baker and Mohler, 2014). Crop rotation becomes more effective when no weed seeds from the neighbouring land invade the field under rotation (González-Díaz et al., 2012). The allelochemicals added to the field from the previous allelopathic crop and the changed management practices together help to control weeds (Mamolos and Kalburtji, 2001). Recent research (Dmitrović et al., 2014) has proven that allelopathic plants fill the soil with allelochemicals, which suppresses weeds in the following crop. In a recent study, *E. crus-galli* was grown on soils obtained after harvest of the allelopathic rice cultivar PI312777 and non-allelopathic (Liaojing-9) rice cultivars (Dmitrović et al., 2014). The soil from allelopathic rice cultivars contained higher concentrations of allelochemicals, which suppressed the growth of *E. crus-galli*. Recently, Tabaglio et al. (2013) suggested the inclusion of a rye crop in a rotation with a maize crop. The purpose was to suppress weeds, such as *P. oleracea* L. and *A. retroflexus* in the following maize crop. Greenhouse experiments confirmed the allelopathic activity of rye litter to suppress weeds through the exudation of allelochemicals, including benzoxazinoids 2,4-dihydroxy-1,4 (2H)-benzoxazin-3-one (DIBOA) and benzoxazolin-2(3H)-one (BOA) (Tabaglio et al., 2013). In conclusion, allelopathic crops included in a rotation help to suppress weeds in the following crop through the exudation of allelochemicals.

6. Conclusions

Allelopathic crops express their allelopathic activity through exudation of allelochemicals. The transport of allelochemicals to target weed species is facilitated by microorganisms. Also, allelochemicals promote the activities of soil microbes, which pose a positive effect on crop plants. Growing allelopathic crop cultivars may become an important way to suppress weeds, especially when used under the umbrella of integrated weed management. Similarly, the use of allelopathic cover crops, allelopathic intercrops, the inclusion of allelopathic crops in rotation, and the use of allelopathic plant residues as mulches are important ways that can be practiced for economical, environment friendly weed management in agricultural systems. The allelopathic potential of crops is desired to be strengthened using conventional and modern plant breeding techniques.

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